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(11)

EP 1 128 188 A2

(12)

## EUROPEAN PATENT APPLICATION

(43) Date of publication:  
29.08.2001 Bulletin 2001/35

(51) Int Cl.7: G01R 33/34

(21) Application number: 01301564.9

(22) Date of filing: 21.02.2001

(84) Designated Contracting States:  
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU  
MC NL PT SE TR  
Designated Extension States:  
AL LT LV MK RO SI

• Demeester, Gordon D.  
Wickliffe, Ohio 44092 (US)  
• Braum, William O.  
Twinsburg, Ohio 44087 (US)

(30) Priority: 24.02.2000 US 513062

(71) Applicant: Marconi Medical Systems, Inc.  
Cleveland, Ohio 44143 (US)

(74) Representative: Waters, Jeffrey  
Marconi Intellectual Property  
Marrable House  
The Vineyards  
Gt. Baddow  
Chelmsford Essex CM2 7QS (GB)

(72) Inventors:  
• Fujita, Hiroyuki  
Highland Heights, Ohio 44143 (US)

### (54) RF coil for magnetic resonance apparatus

(57) A tunable radio frequency birdcage coil (30) is oriented vertically in a bore-type magnetic resonance apparatus. The birdcage coil (30) includes a pair of end rings (60, 62) disposed in parallel planes along a coil axis which is orthogonal to the main magnetic field. A plurality of rungs (64) electrically interconnect the end rings (60, 62) to form a generally cylindrical volume. The end rings (60, 62) and rungs (64) are mounted on a hinged (68) dielectric former (66). Conductive connectors (70) releasably fasten the end rings (60, 62) so that the coil (30) may be opened and closed to receive a portion of a subject to be examined. A conductive loop (80) is inductively coupled and positioned parallel to the end rings (60, 62). The conductive loop (80) is slidably adjustable along the coil axis for matching and tuning end-ring modes of the coil. The coil is oriented to provide a subject disposed therein with an open view for fMRI applications. Means for stimulating the visual senses (100) is mounted adjacent the examination region (14) to facilitate fMRI applications.

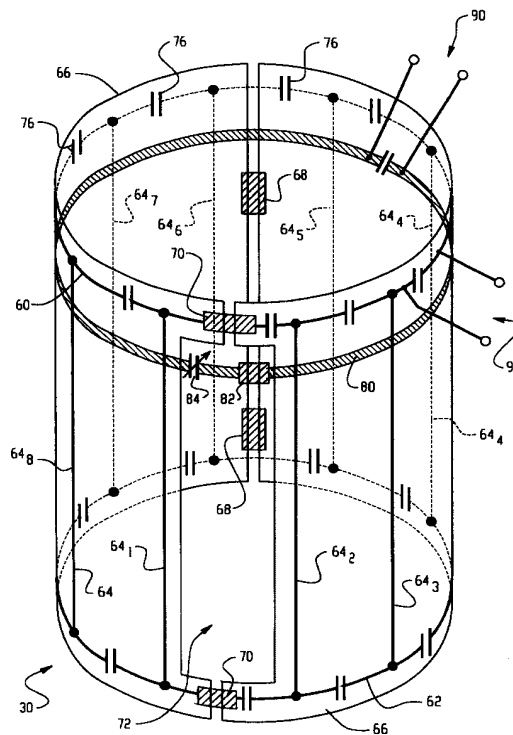


Fig. 2

## Description

**[0001]** The present invention relates to magnetic resonance apparatus. It finds particular application in conjunction with medical diagnostic imaging and will be described with particular reference thereto. It is to be appreciated, however, that the invention may find further application in quality control inspections, spectroscopy, and the like.

**[0002]** Conventionally, magnetic resonance systems generate a strong, temporally constant main magnetic field, commonly denoted  $B_0$ , in a free space or bore of a magnet. This main magnetic field polarizes the nuclear spin system of an object. Nuclear spins of the object then possess a macroscopic magnetic moment vector preferentially aligned with the direction of the main magnetic field. In a superconducting annular magnet, the  $B_0$  magnetic field is generated along the longitudinal axis of the cylindrical bore, which is assigned to be the z-axis. In an open system, the  $B_0$  magnetic field is oriented vertically between a pair of pole pieces, which is assigned to be the z-axis.

**[0003]** To generate a magnetic resonance signal, the polarized spin system is excited at resonance by applying a radio frequency (RF) magnetic field  $B_1$ , with a vector component perpendicular to that of the  $B_0$  field. In a transmission mode, the radio frequency coil is pulsed to tip the magnetization of the polarized sample away from the z-axis. As the magnetization precesses around the z-axis, the precessing magnetic moment generates a magnetic resonance signal at the Larmor frequency which is received by the same or another radio frequency coil in a reception mode.

**[0004]** Birdcage coils are often used to excite and/or receive magnetic resonance signals, especially in horizontal field or bore-type MRI systems, because of the good  $B_1$  uniformity over a large field of view. In bore-type systems, the axis of the birdcage coil is typically aligned with the z-axis and the resident resonant current that generates the circularly polarized  $B_1$  field is sampled as an orthogonal pair of transverse modes.

**[0005]** However, aligning the coil axis with the  $B_0$  field in a bore-type machine can be problematic. Often, patients experience feelings of claustrophobia during head imaging applications due to the proximity of the birdcage coil to the patient's face. In addition, aligning the coil axis with the horizontal  $B_0$  field hampers fMRI (functional magnetic resonance imaging) applications, which require additional space near the patient's face for devices to stimulate the visual senses.

**[0006]** In accordance with one aspect of the present invention, an RF coil assembly for a magnetic resonance apparatus is provided. The magnetic resonance apparatus includes a main magnet which generates a temporally constant and substantially uniform main magnetic field along a main magnetic field axis through an examination region. A radio frequency (RF) transmitter and the RF volume coil assembly perform at least

one of exciting magnetic resonance dipoles within the examination region and receiving magnetic resonance signals from the resonating dipoles. A receiver receives and demodulates the magnetic resonance signals. The RF volume coil assembly includes a pair of end rings interrupted by a plurality of reactive elements. The end rings are disposed in displaced parallel planes along a coil axis which is orthogonal to the main magnetic field axis and which operate in an end ring mode. A plurality of spaced rungs which electrically interconnect the end rings operate in a transverse mode and define a generally cylindrical volume. The end rings and rungs are supported by a dielectric former which has separable portions. The RF volume coil further comprises a conductive loop which is inductively coupled to the end rings.

**[0007]** In accordance with another aspect of the present invention, a method for magnetic resonance imaging of a portion of a patient disposed along a subject axis includes opening an RF volume coil having a coil axis along a hinged portion parallel to the coil axis. The method further includes introducing a portion of the subject to be examined into the RF volume coil and closing the hinged RF volume coil to enclose the portion of the subject to be examined within the coil. An examined portion of the subject is positioned in an examination region with the coil axis orthogonal to the subject axis and a main magnetic field is generated parallel to and along the subject axis through the examination region. RF signals are transmitted into the examined subject portion to induce magnetic resonance in nuclei and magnetic resonance signals are received using the RF volume coil. At least a first, transverse resonant mode signal and a second, end ring resonant mode signal are extracted from the RF volume coil and reconstructed into an image representation.

**[0008]** One advantage of the present invention is that any patient claustrophobia can be reduced.

**[0009]** Another advantage of the present invention is that it can provide quadrature capability using an end-ring mode and sinusoidal mode.

**[0010]** Another advantage of the present invention resides in its applicability to fMRI applications.

**[0011]** Yet another advantage of the present invention is that it permits a full volume RF coil to be constructed offering good  $B_1$  uniformity regardless of  $B_0$  field orientation.

**[0012]** Ways of carrying out the invention will now be described in detail, by way of example, with reference to the accompanying drawings, in which:

FIGURE 1 is a diagrammatic illustration of a magnetic resonance system in accordance with the present invention;

FIGURE 2 is a diagrammatic illustration of an exemplary RF birdcage coil with uniformly spaced rungs in accordance with the present invention;

FIGURE 3 is a diagrammatic illustration of an exemplary RF birdcage coil with non-uniformly spaced rungs in accordance with the present invention; and

FIGURE 4 is a top perspective view of an open view RF birdcage coil in accordance with the present invention.

**[0013]** With reference to FIGURE 1, a main magnetic field control **10** controls superconducting or resistive magnets **12** such that a substantially uniform, temporally constant main magnetic field  $B_0$  is created along a z-axis through an examination region **14**. Although a bore-type magnet is illustrated in FIGURE 1, it is to be appreciated that the present invention is applicable to open or vertical field magnetic systems as well. A magnetic resonance sequence applies a series of radio frequency (RF) and magnetic field gradient pulses to invert or excite magnetic spins, induce magnetic resonance, refocus magnetic resonance, manipulate magnetic resonance, spatially and otherwise encode the magnetic resonance, to saturate spins, and the like to generate magnetic resonance imaging and spectroscopy sequences. More specifically, gradient pulse amplifiers **20** apply current pulses to selected ones or pairs of whole body gradient coils **22** to create magnetic field gradients along x, y, and z-axes of the examination region **14**. A radio frequency transmitter **24**, preferably digital, transmits radio frequency pulses or pulse packets to a whole-body RF birdcage coil **26** to generate  $B_1$  magnetic fields within the examination region. A typical radio frequency pulse is composed of a packet of immediately contiguous pulse segments of short duration which, taken together with each other and any applied gradients, achieve the selected magnetic resonance manipulation. The RF pulses are used to saturate, excite resonance, invert magnetization, refocus resonance, or manipulate resonance in selected portions of the examination region. For whole-body applications, the resonance signals are commonly picked up in quadrature by the whole-body RF birdcage coil **26**.

**[0014]** Local coils are commonly placed contiguous to selected regions of the subject for generating radio frequency pulses into and/or receiving induced magnetic resonance signals from the selected regions. A birdcage coil **30** is one type of local coil used in magnetic resonance applications. Preferably, the local radio frequency birdcage coil **30** receives magnetic resonance signals emanating from the selected region. The resultant radio frequency signals are picked up in quadrature by the local RF coil **30** or other specialized RF coils and demodulated by a receiver **38**, preferably a digital receiver.

**[0015]** A sequence control processor **40** controls the gradient pulse amplifiers **20** and the transmitter **24** to generate any of a plurality of magnetic resonance imaging and spectroscopy sequences, such as echo-planar imaging, echo-volume imaging, gradient and spin echo

imaging, fast spin echo imaging, and the like. For the selected sequence, the receiver **38** receives a plurality of data lines in rapid succession following each RF excitation pulse. An analog-to-digital converter **42** converts each data line to a digital format. The analog-to-digital converter **42** is disposed between the radio frequency receiving coil and the receiver for digital receivers and is disposed downstream (as illustrated) from the receiver for analog receivers. Ultimately, the demodulated radio frequency signals received are reconstructed into an image representation by a reconstruction processor **50** which applies a two-dimensional Fourier transform or other appropriate reconstruction algorithm. The image may represent a planar slice through the patient, an array of parallel planar slices, a three-dimensional volume, or the like. The image is then stored in an image memory **52** where it may be accessed by a display **54**, such as a video monitor, active matrix monitor, or liquid crystal display, which provides a human-readable display of the resultant image.

**[0016]** With reference to FIGURE 2 and continued reference to FIGURE 1, the RF birdcage coil **30** includes a pair of end rings **60, 62** which are disposed in a parallel and spaced-apart relation. The end rings **60, 62** are electrically interconnected by spaced legs or rungs **64<sub>1</sub>, ..., 64<sub>8</sub>** to form a generally cylindrical volume. For structural stability and manufacturing simplicity, the birdcage coil **30** is constructed on a dielectric support or former **66** which is cylindrical in shape. As will be described more fully below, sections of the former may be removed to provide openness. In the preferred embodiment, the dielectric former **66** is constructed of resin-bonded fiberglass, ABS, or another plastic with low dielectric loss which does not contain free protons or other dipoles and in which magnetic resonance will be induced. In one embodiment, the end rings **60, 62** and rungs **64<sub>1</sub>, ..., 64<sub>8</sub>** are copper foil strips. These copper strips are fastened to the former **66** in a configuration corresponding to the preferred birdcage coils.

**[0017]** With reference to FIGURE 2 and FIGURE 3, in one preferred embodiment, the RF birdcage coil **30** contains eight evenly-spaced rungs **64<sub>1</sub>, ..., 64<sub>8</sub>**, as illustrated in FIGURE 2. In this embodiment, each adjacent pair of rungs subtends an angle of 45 degrees on each end ring **60, 62**. In a second preferred embodiment, the RF birdcage coil **30** contains twelve non-uniformly spaced rungs **64<sub>1</sub>, ..., 64<sub>12</sub>**, as illustrated in FIGURE 3. In both the eight-rung embodiment and twelve-rung embodiment, it is to be appreciated that a larger or smaller number of rungs may be employed. Those skilled in the art will appreciate that increasing the number of rungs on the coil increases the  $B_1$  uniformity of the transverse or sine modes of the birdcage coil.

**[0018]** In one embodiment, the dielectric former **66** is hinged with a plurality of hinges **68** such that the coil may be opened to receive a portion of a subject to be examined. Conductive connectors **70** releasably fasten the coil for opening the coil and closing it around a por-

tion of a subject disposed therein. Preferably, the connectors **70** are in electrical communication with the end rings **60, 62**, as illustrated in FIGURES 2 and 3. The connectors **70** are conductive clips, snaps, or other friction fit fasteners which do not alter significantly the impedance of each end ring. In another embodiment, the dielectric former **66** pulls apart completely into two substantially equal halves. In this embodiment, no hinges are employed. Rather, conductive connectors, as described above, are located on opposite sides of the coil in electrical communication with the end rings.

**[0019]** As illustrated in FIGURE 2, the rungs **64<sub>1</sub>, ..., 64<sub>8</sub>**, of the evenly-spaced eight-rung embodiment are spaced wide enough to accommodate a portion of the subject to be examined between two adjacent rungs. In addition, the dielectric former **66** includes a subject entry gap or opening **72** between two adjacent rungs **64<sub>1</sub>, 64<sub>2</sub>** for receiving the portion of the subject to be examined. For example, in head imaging applications, a subject's neck may be disposed between two adjacent rungs **64<sub>1</sub>, 64<sub>2</sub>**. Such a head imaging application is illustrated in FIGURE 4.

**[0020]** As illustrated in FIGURE 3, the rungs **64<sub>1</sub>, ..., 64<sub>12</sub>**, of the twelve-rung embodiment are spaced non-uniformly such that a circumferential space between an adjacent pair of rungs **64<sub>1</sub>, 64<sub>2</sub>** is wide enough to accommodate a portion of the subject to be examined. The circumferential space between the two adjacent rungs **64<sub>1</sub>, 64<sub>2</sub>** is wider than the space between any other two adjacent rungs on the coil. In this embodiment, the dielectric former **66** also includes a subject entry gap **72** between the two adjacent rungs **64<sub>1</sub>, 64<sub>2</sub>** for receiving the portion of the subject to be examined. Again, FIGURE 4 illustrates a head imaging application utilizing the aforementioned features of the present invention.

**[0021]** As is known generally in the art, the rungs **64** are sensitive to  $B_1$  fields orthogonal to the axis of the coil, which is illustrated in FIGURE 1 as oriented along the y-axis. In other words, the rungs are inherently sensitive to the transverse, circularly polarized  $B_1$  field which is orthogonal to the  $B_1$  field of the end-ring mode, which is parallel to the coil axis. Accordingly, when the end-ring mode and a conventional sinusoidal/cosinusoidal resonant mode are tuned to the same frequency, three-axis performance is achieved. More commonly, only the end ring mode and a sinusoidal mode orthogonal to the  $B_0$  field are utilized.

**[0022]** Reactive elements, preferably capacitors **76**, interrupt the end rings **60, 62** of the coil. The capacitors are provided to tune the conventional sinusoidal/cosinusoidal resonant modes, as is known generally in the art. While capacitive elements **76** are illustrated in the end rings **60, 62**, those skilled in the art will recognize that capacitive elements may be alternatively or conjunctively located in the rungs **64** to achieve lowpass, bandpass, or highpass operation.

**[0023]** Tuning of the end-ring mode is not as straightforward. In order to tune the end-ring mode to typical

frequencies, an electrically conductive loop **80** is inductively coupled to the end rings **60, 62**. Like the end rings **60, 62**, the conductive loop **80** is releasably fastened with a conductive connector **82**. As described above, the conductive connector **82** may be a conductive clip, snap, or other friction fit fastener which does not alter significantly the impedance of the conductive loop **80**. The conductive loop **80** is tuned or matched to the desired frequency by sliding the loop longitudinally along the axis of the coil until the optimal condition for the end-ring mode operation is met. At least one variable capacitance **84** interrupts the loop **80** to aid in tuning to the desired frequency with appropriate matching. In one embodiment, the conductive loop **80** is a copper foil strip.

**[0024]** As illustrated in FIGURES 2 and 3, resonant signals associated with each detectable  $B_1$  field are communicated to the receiver **38** through sampling ports **90**. One skilled in the art will appreciate that three-axis performance is achievable by such a birdcage coil. The availability of three resonant modes, tuned to a common frequency, enables operators to place the coil in any desired orientation, irrespective of  $B_0$  field direction, and receive usable signals. Moreover, it is to be appreciated that the coil may operate with two orthogonal modes tuned to the same frequency, while the end ring mode may be sampled for spectroscopy applications at a different frequency.

**[0025]** Referring back to FIGURE 4 and FIGURE 1, the birdcage coil is preferably oriented with its coil axis orthogonal to a horizontally-directed  $B_0$  magnetic field. With the birdcage coil in this orientation and a subject disposed in the bore of the magnet for a head imaging application, open space exists outside of the coil in front of the patient's face. For such an application, the patient can see through the end of the coil as illustrated in FIGURE 4. This open-view feature of the birdcage coil accommodates devices for stimulating the visual senses. Such means for stimulating the visual senses **100** is mounted above the birdcage coil in the subject's line of sight as shown in FIGURE 1. Stimulation of the visual senses by an external source allows for fMRI studies of a subject. Those skilled in the art will appreciate that in such fMRI studies, the patient's visual, audio, and/or olfactory senses may be stimulated while head scan data is collected. In another embodiment, the coil may be adapted to accommodate audio devices for additional fMRI applications.

## Claims

1. An RF coil assembly for a magnetic resonance apparatus having a main magnet (**12**) for generating a main magnetic field along a main magnetic field axis through an examination region (**14**), a radio frequency (RF) transmitter (**24**) and RF coil assembly (**30**) arranged to perform at least one of exciting

- magnetic resonance dipoles within the examination region (14) and receiving magnetic resonance signals from the resonating dipoles, and a receiver (38) for receiving and demodulating the magnetic resonance signals, the RF coil assembly (30) comprising: a pair of end rings (60, 62) interrupted by a plurality of reactive elements (76), said end rings (60, 62) disposed in displaced parallel planes along a coil axis, said coil axis being orthogonal to the main magnetic field axis, the end rings being arranged for operation in an end ring mode; a plurality of spaced rungs (64<sub>1</sub>, ..., 64<sub>8</sub>) electrically interconnecting said end rings (60, 62) to define a generally cylindrical volume, the spaced rungs being arranged for operation in a transverse mode; a dielectric former having separable portions, said end rings (60, 62) and said rungs (64<sub>1</sub>, ..., 64<sub>8</sub>) being supported by the dielectric former (66); and a conductive loop (80) inductively coupled to the end rings (60, 62).
2. An RF coil assembly as claimed in claim 1, wherein the dielectric former (66) is hinged with a plurality of hinges (68) such that the RF volume coil (30) is adapted to be opened to receive a portion of a subject to be examined.
  3. An RF coil assembly as claimed in claim 1 or claim 2, wherein separable portions of the RF coil assembly (30) are fastened together by a plurality of conductive connectors (82), said connectors (82) being in electrical communication with the end rings (60, 62).
  4. An RF coil assembly as claimed in any one of claims 1 to 3, wherein the conductive loop (80) is configured in sections supported by the dielectric former (66), a conductive connector (70) connecting the conductive loop (80) sections.
  5. An RF coil assembly as claimed in claim 4, wherein the conductive loop (80) is (i) interrupted by at least one variable capacitive element (76); and (ii) is slidably disposed along the coil axis.
  6. An RF coil assembly as claimed in any one of claims 1 to 5, wherein: an adjacent pair of said rungs (64<sub>1</sub>, 64<sub>2</sub>) are spaced to accommodate therebetween a portion of a subject to be examined; and the dielectric former (66) defines a subject entry gap (72) between the two adjacent rungs (64<sub>1</sub>, 64<sub>2</sub>) mounted to the former (66) to facilitate receipt of the portion of the subject to be examined.
  7. An RF coil assembly as claimed in any one of claims 1 to 6, wherein: the plurality of rungs (64<sub>1</sub>, ..., 64<sub>8</sub>) are not uniformly spaced such that an adjacent pair of said rungs (64<sub>1</sub>, 64<sub>2</sub>) are spaced to accommodate therebetween a portion of a subject to be examined; and the dielectric former (66) includes a subject entry gap (72) between the wide-spaced pair of rungs (64<sub>1</sub>, 64<sub>2</sub>) through which a portion of the subject is received.
  8. An RF coil assembly as claimed in any one of claims 1 to 7, further comprising: means for stimulating at least one of the visual, audio, and olfactory senses of a subject disposed adjacent the examination region (14); and wherein the RF coil assembly (30) is oriented such that a subject whose head is disposed within the RF coil assembly (30) views the means for stimulating the visual senses (100) through one end ring (60, 62) of the RF coil assembly (30).
  9. Magnetic resonance apparatus comprising a main magnet (12) for generating a main magnetic field along a main magnetic field axis through an examination region (14), a radio frequency (RF) transmitter (24) and RF coil assembly (30) arranged to perform at least one of exciting magnetic resonance dipoles within the examination region (14) and receiving magnetic resonance signals from the resonating dipoles, and a receiver (38) for receiving and demodulating the magnetic resonance signals, including an RF coil assembly as claimed in any one of claims 1 to 8.
  10. A method for magnetic resonance imaging of a portion of a subject disposed along a subject axis, said method including:
    - (a) opening a RF volume coil (30) having a coil axis along a hinged (68) portion parallel to the coil axis;
    - (b) introducing a portion of the subject to be examined into the RF volume coil (30);
    - (c) closing the hinged (68) RF volume coil (30) to enclose the portion of the subject to be examined within the coil (30);
    - (d) positioning an examined portion of the subject in an examination region (14) with the coil axis orthogonal to the subject axis;
    - (e) generating a main magnetic field parallel to and along the subject axis through the examination region (14);
    - (f) transmitting RF signals into the examined subject portion to induce magnetic resonance in nuclei;
    - (g) receiving (38) the magnetic resonance signals using the RF volume coil (30);
    - (h) extracting at least a first transverse resonant mode (90) signal and a second end ring resonant mode (90) signal from the RF volume coil (30); and
    - (i) reconstructing (50) the magnetic resonance

signals into an image representation.

11. A method as claimed in claim 10, wherein the extracting step includes: inductively coupling a conductive loop (80) to end rings (60, 62) of the coil (30) to pick-up an end-ring resonant mode signal as the second resonant mode signal; and matching the end ring resonant mode (90) signal and the first transverse resonant mode signal to a common frequency by at least one of (i) adjusting at least one of a position and a capacitance of the conductive loop (80) to the end rings (60, 62); and (ii) adjusting an effective reactance of the RF volume coil (30) such that the end ring resonant mode (90) signal and the first transverse resonant mode (90) signal occur at the common frequency.

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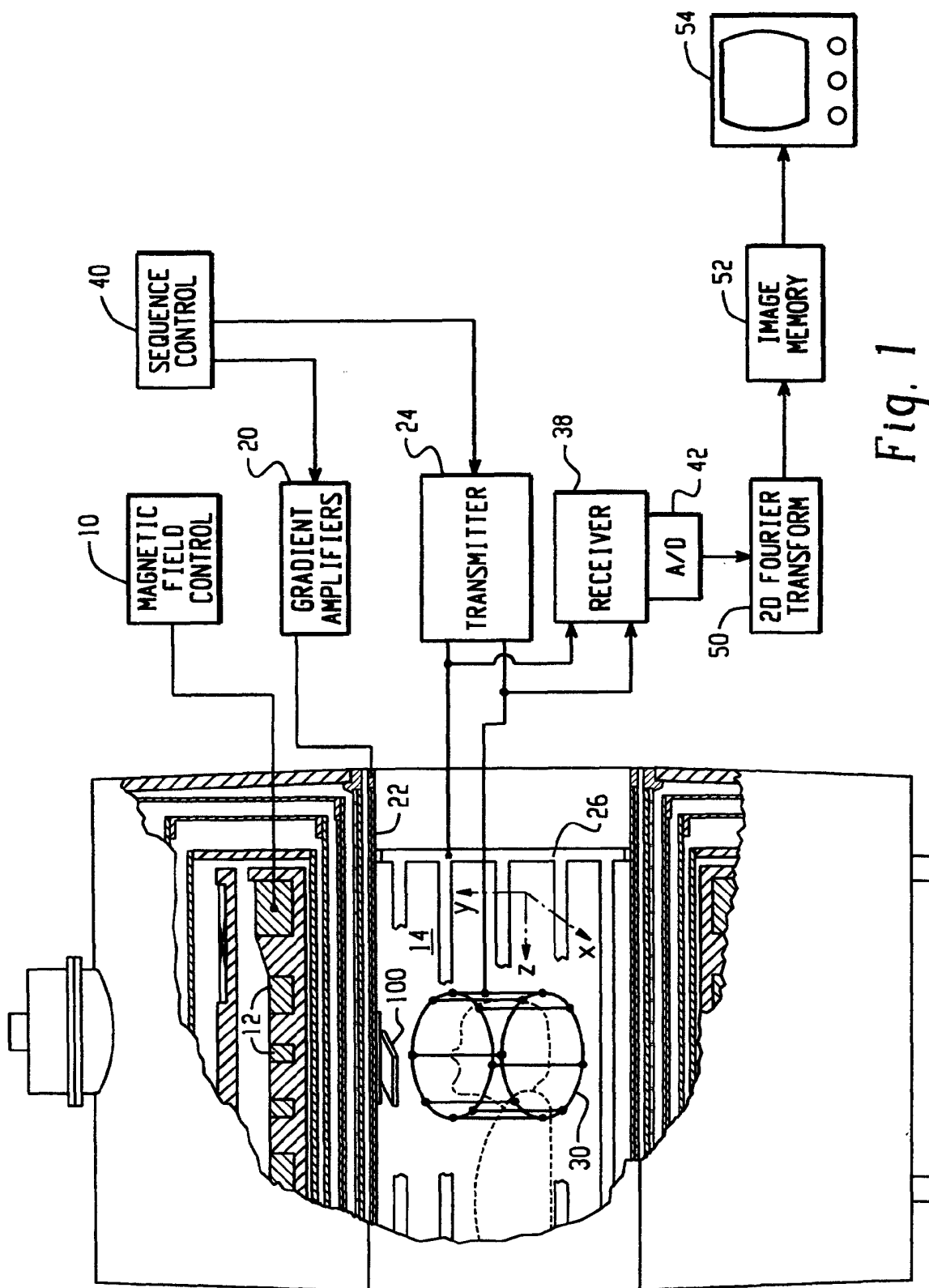
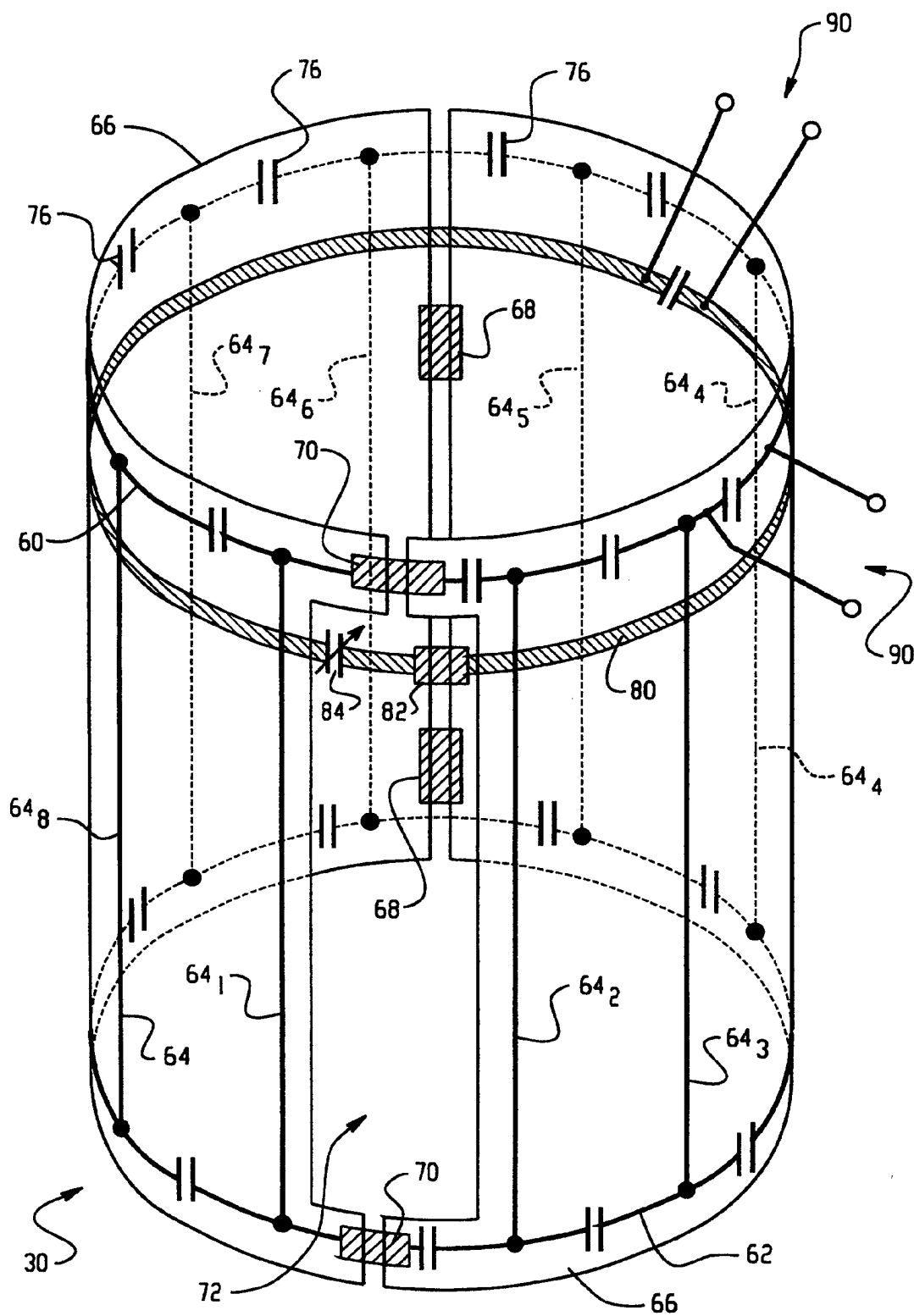
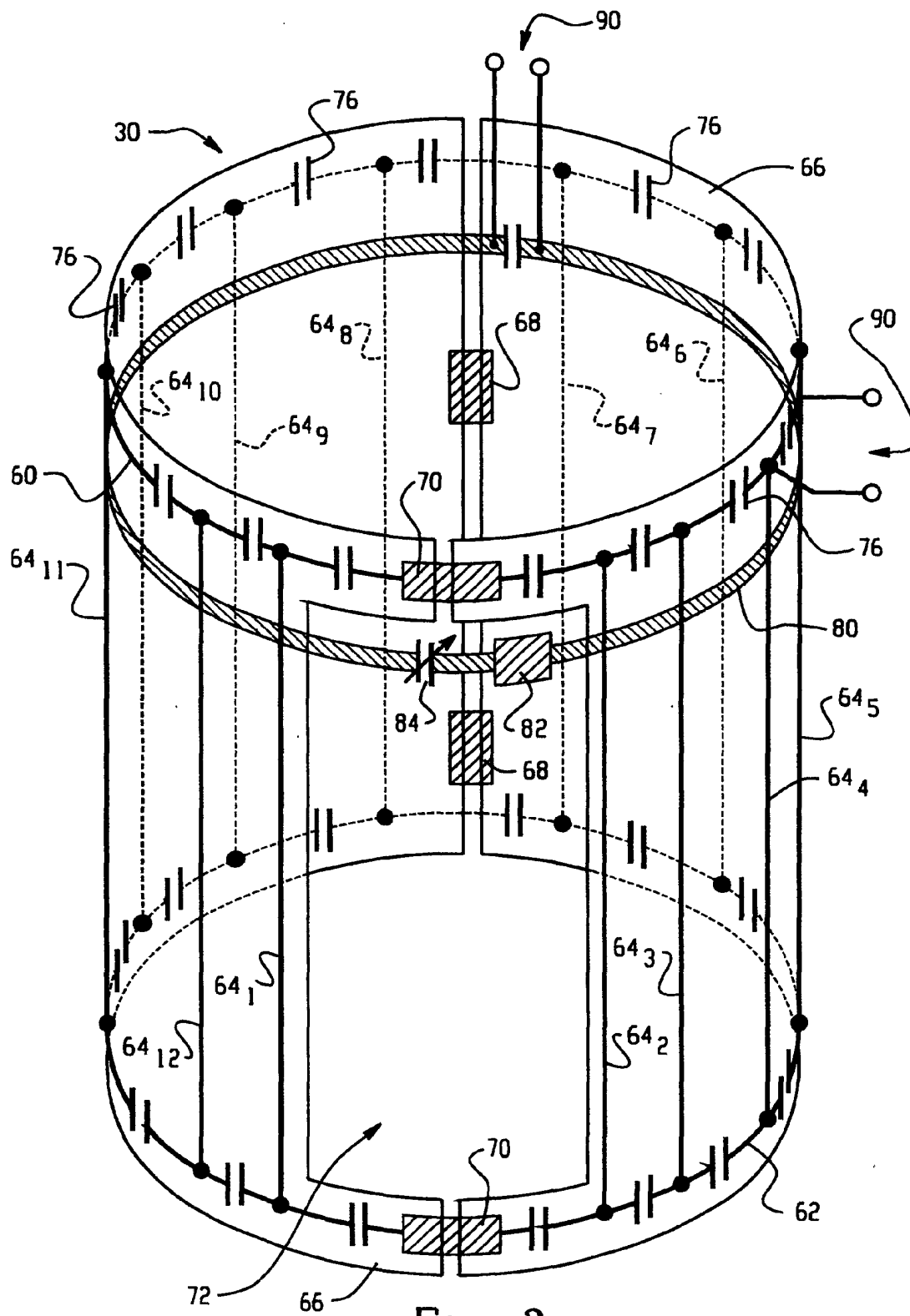


Fig. 1



*Fig. 2*



*Fig. 3*

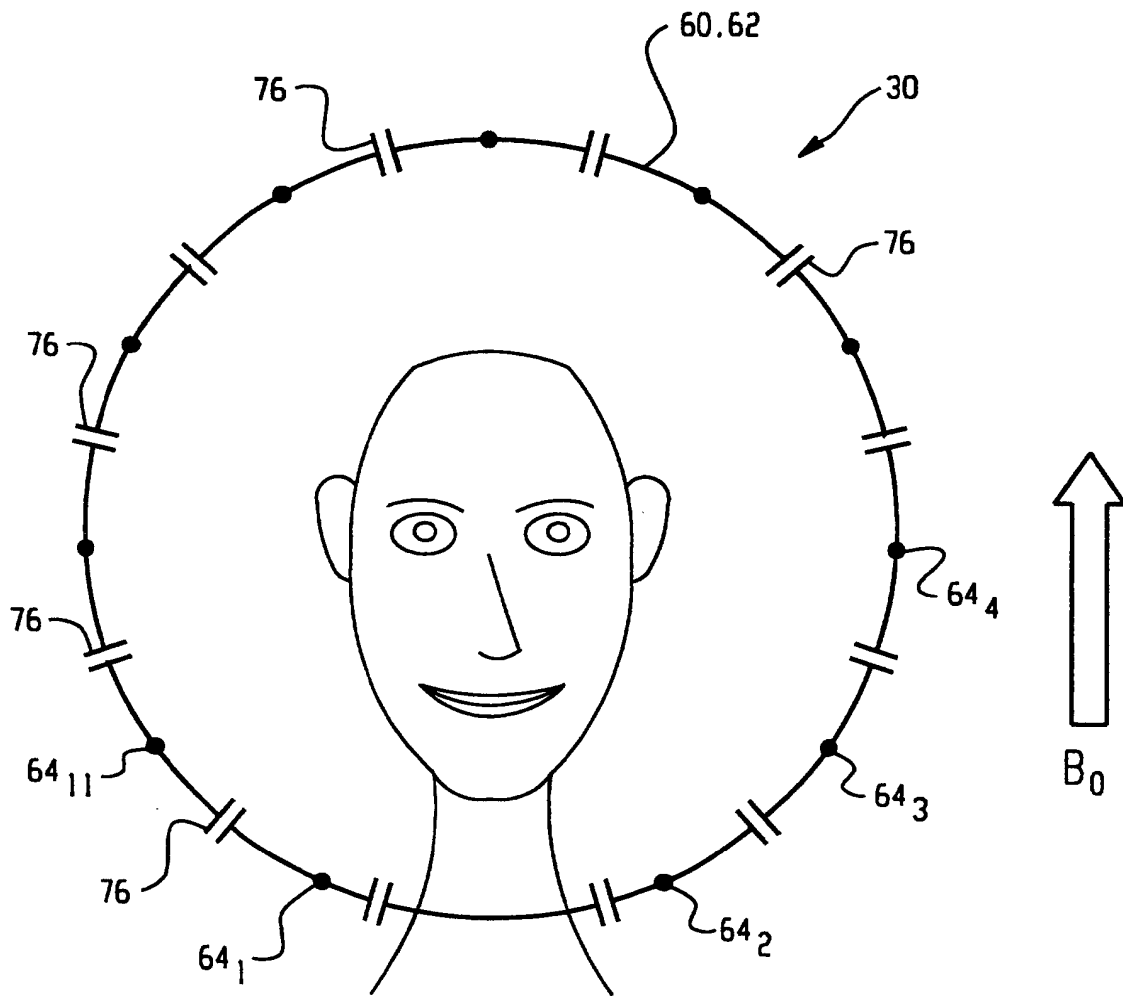


Fig. 4